Executable Specifications

Foundations of Software Engineering
http://msrweb/foundations
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The group

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Jan. 1999

Jan. 2000

Jan. 2001

Jan. 2002

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Partners

- BizTalk
- Hailstorm
- Indigo
- ITE (formerly TMT)
- Netconfig
- Palladium (formerly Trusted Windows)
- ...

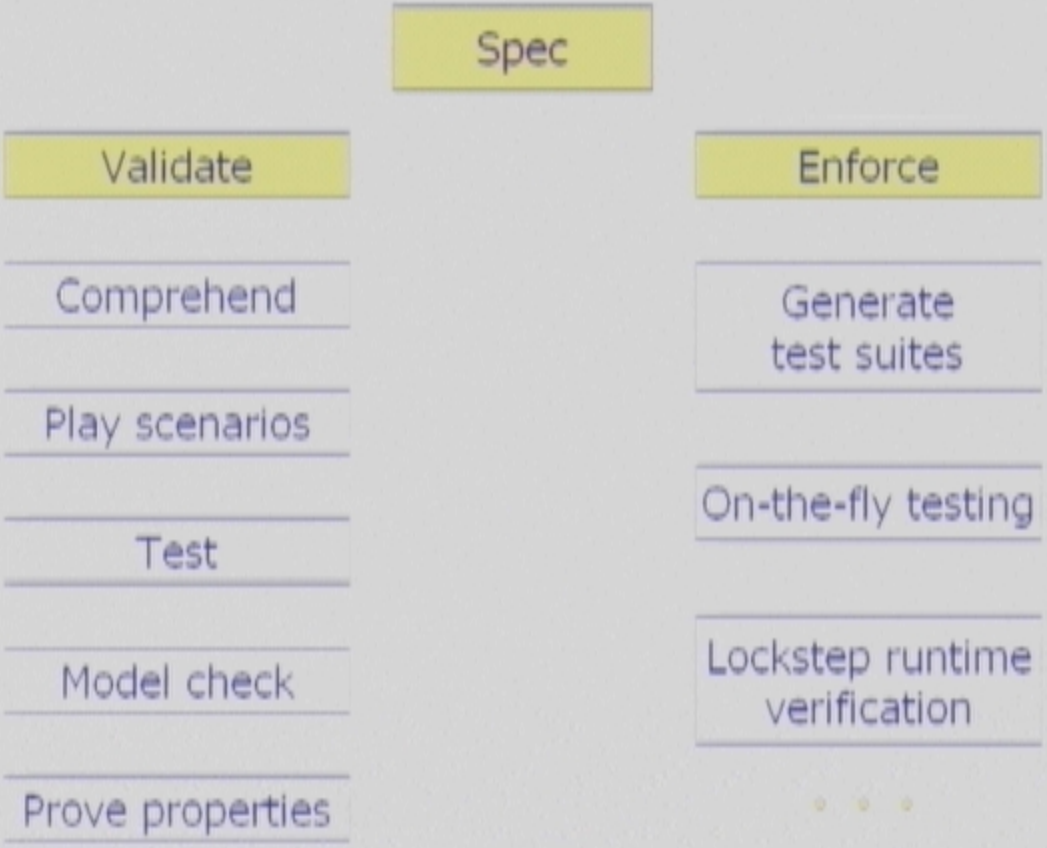
Problems we solve

- Poor specifications
  - Unenforceable
  - Poorly documented
- Growing spec. vs implementation gap
- High cost of design bugs
- Problems with testing
  - starts late in the process
  - often fails to test the intended functionality
  - is insufficiently automated

Our approach

Rigorous executable comprehensible spec

- Validate the design
  - Comprehend
  - Play scenarios
  - Test, model-check
  - Prove properties
- Enforce the spec
  - Generate test suites algorithmically
  - Use conformance execution


Spec
Validate
Enforce
Comprehend
Play scenarios
Test
Model check
Prove properties
Generate test suites
On-the-fly testing
Lockstep runtime verification

Conventional wisdom

- Specification should be declarative. Exec. spec is a contradiction in terms.
  - If you can execute the spec then why would you bother to implement it?
  - If you can execute the spec then it got to be full of irrelevant details, too specific, too low level.
- In fact, exec specs make sense

Example: topological sorting

- Given an acyclic digraph G = (V,E), arrange the vertices into a sequence S where each edge (u,v) leads forward.
- Observe: there is a vertex without incoming edges, and the remaining digraph is acyclic.
- Topsort: Use the observation repeatedly to build the desired sequence S.

Topsort

- A Modula-2 implementation by Niklaus Wirth
- An AsmL spec (a more OO version)

topsort_mod.txt - Notepad

File Edit Format View Help

```
(* Read a sequence of relations defining a directed, finite
   graph.  Then establish whether or not a partial ordering
   is defined.  If so, print the element in a sequence showing
   the partial ordering. (Topological sorting)  *)

MODULE topsort;

FROM InOut   IMPORT WriteLn, WriteCard, ReadCard, WriteString;
FROM Storage IMPORT ALLOCATE;

TYPE lref = POINTER TO leader;

     tref = POINTER TO trailer;

     leader = RECORD
                key: CARDINAL;
                count: CARDINAL;
                trail: tref;
                next: lref;
              END;

     trailer = RECORD
                 id: lref;
                 next: tref
               END;

VAR head,tail,p,q: lref;
```

Topological Sorting

```
class Vertex
```

This is an abstract class at this point - no fields or methods. We don't know what vertices are.

```
var V as Set of Vertex
var E as Set of (Vertex,Vertex)
var S as Seq of Vertex = []

topsort()
  step until fixpoint
    let X = V difference asSet(S)
    if X <> {} then
      S := S + [(any v | v in X where not exists u in X where E(u,v))]
```

In order to print vertices, we endow Vertex with an integer field and a printing method.

```
class Vertex...
  key as Integer
  asString() as String
    return "v" + asString(key)
```

We provide a particular input for the demo.

```
initializeDigraph()
  let N = [new Vertex(i) | i in [0..9]]
  V := asSet(N)
  E := {(N(6),N(0)),(N(2),N(0)),(N(8),N(2)), (N(8),N(1)), (N(8),N(2)),
        (N(5),N(1)),(N(1),N(0)),(N(9),N(1)),(N(9),N(4)),(N(4),N(0)),
        (N(7),N(3))/,(N(2),N(7))
}
```

This is the graphical form of the same.

Topological Sorting

```
class Vertex
```

This is an abstract class at this point - no fields or methods. We don't know what vertices are.

```
var V as Set of Vertex
var E as Set of (Vertex,Vertex)
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class Vertex...
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initialiseDigraph()
  let N = [new Vertex(i) | i in [0..9]]
  V := asSet(N)
  E := {(N(6),N(0)),(N(2),N(0)),(N(8),N(2)), (N(5),N(1)), (N(5),N(2)),
        (N(7),N(7)),(N(7),N(5)),(N(9),N(7)),(N(9),N(4)),(N(4),N(5)),
```

```
class Vertex...
  key as Integer
  asString() as String
    return "v" + asString(key)
```

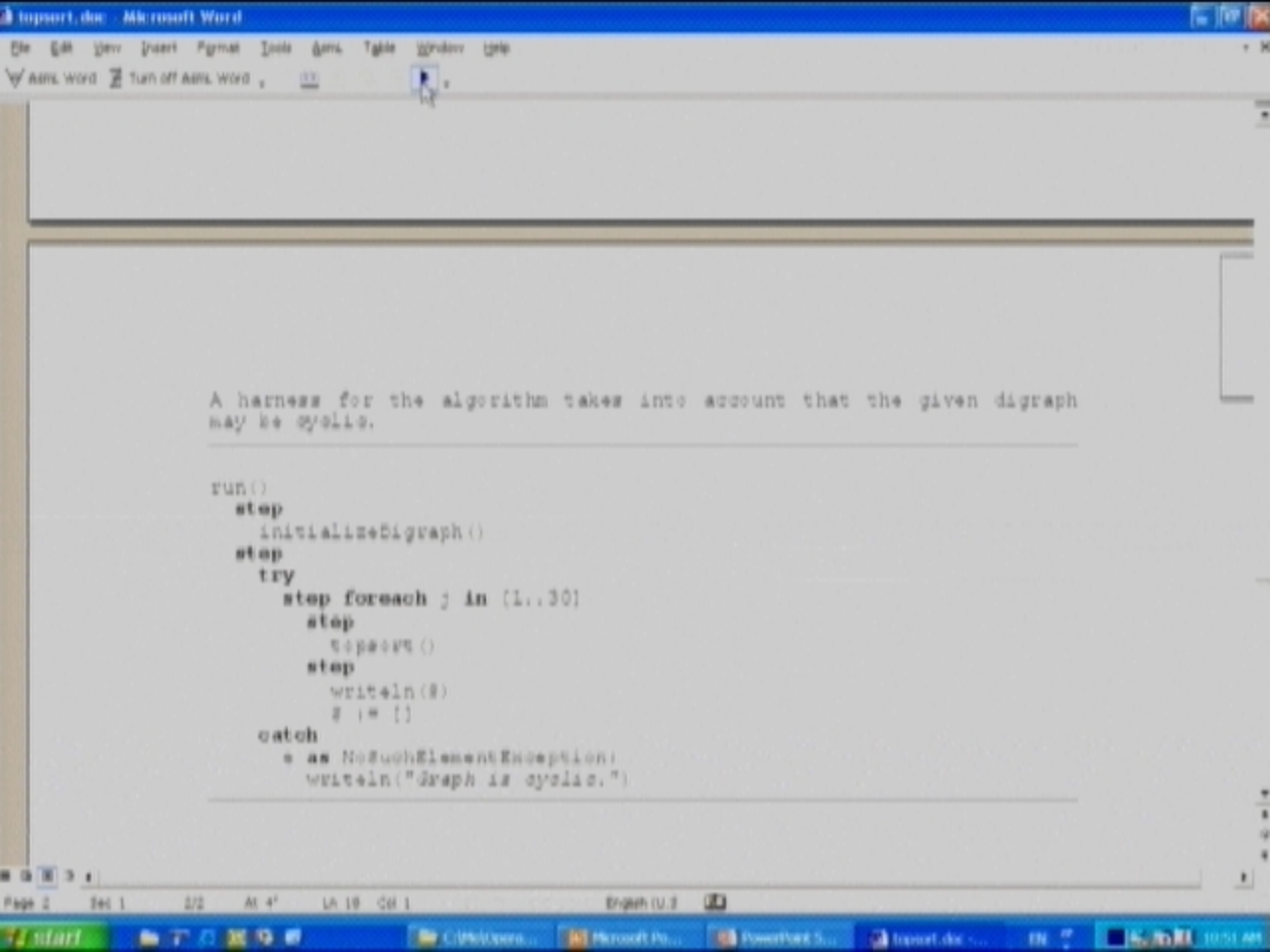
We provide a particular input for the demo:

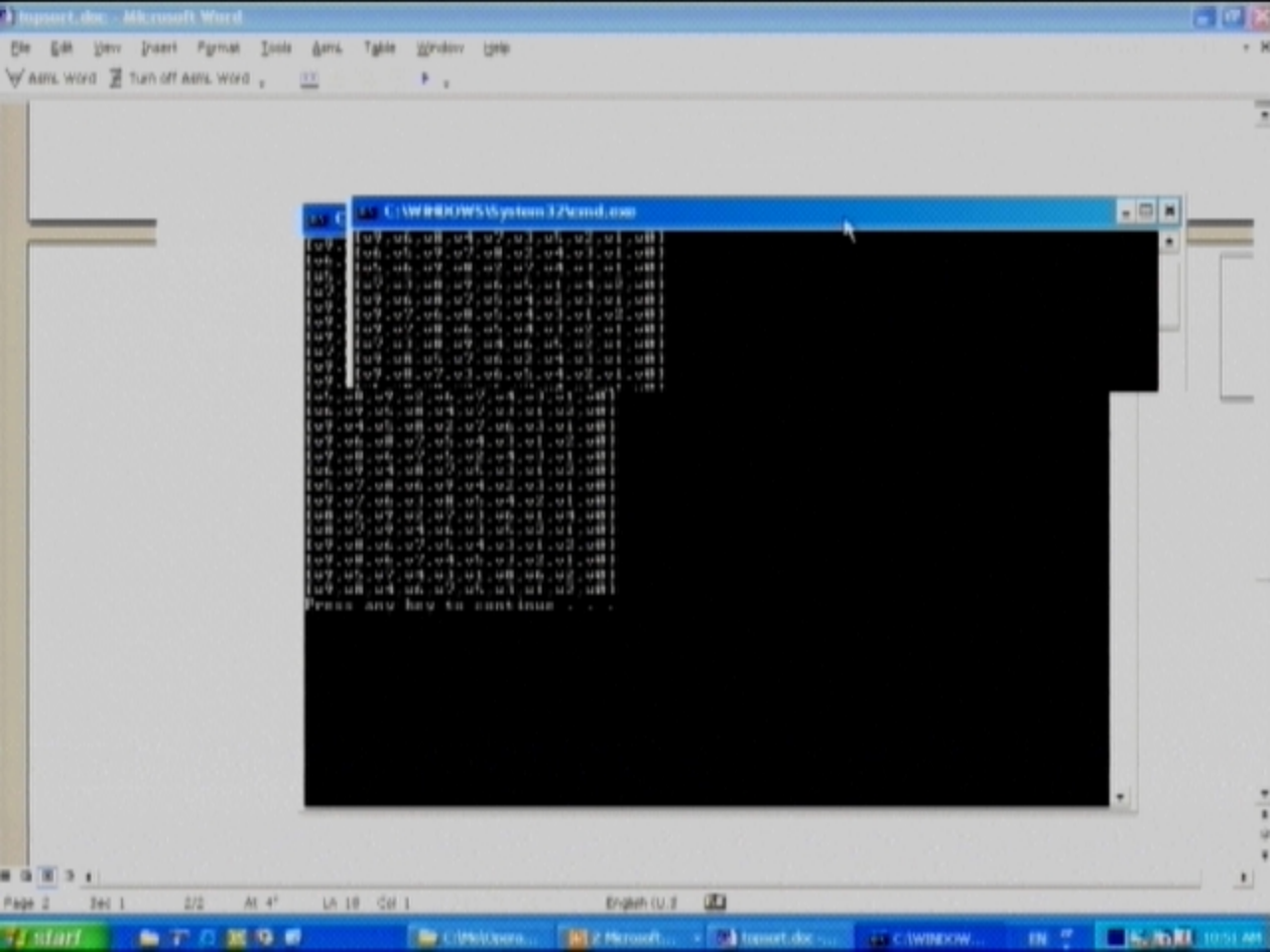
```
initialiseDigraph()
  let N = [new Vertex(i) | i in [0..9]]
  V := asSet(N)
  E := {(N(6),N(0)),(N(2),N(0)),(N(6),N(2)), (N(6),N(1)), (N(6),N(2)),
        (N(3),N(1)),(N(1),N(0)),(N(9),N(1)),(N(9),N(4)),(N(4),N(0)),
        (N(7),N(3))//,(N(0),N(7))
)
```

This is the graphical form of the same.

A harness for the algorithm takes into account that the given digraph may be cyclic.

```
run()
  step
    initialiseDigraph()
  step
    try
      step foreach j in [1..30]
        step
          toposort()
        step
          writeln(0)
          0 := []
    catch
      e as NoSuchElementException!
        writeln("Graph is cyclic.")
```


topsort.doc - Microsoft Word
File Edit View Insert Format Tools Table Window Help
Add-ins Word Turn off Add-in Word
A harness for the algorithm takes into account that the given digraph may be cyclic.
run()
step
initializeDigraph()
step
try
step foreach j in [1..30]
step
topsort()
step
writeln(#)
# := []
catch
e as NoSuchElementException:
writeln("Graph is cyclic.")
Page 2 Sec 1 2/2 At 4" Ln 10 Col 1 English (U.S
start
EN
10:51 AM


C:\WINDOWS\system32\cmd.exe
Press any key to continue . . .

This is the graphical form of

C:\WINDOWS\System32\cmd.exe

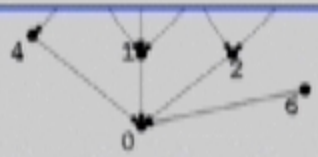
Press any key to continue . . .

```
  key as Integer
  asString() as String
    return "v" + asString(key)

We provide a particular input for the demo.

initializeDigraph()
  let H = [new Vertex(i) | i in [0..9]]
  V := asSet(H)
```

Axiom Compiler



```
  key as Integer
  asString() as String
    return "v" + asString(key)

We provide a particular input for the demo.

initializeDigraph()
  let N = [new Vertex(i) | i in [0..9]]
  V := asSet(N)
```

Aarst Compiler

Output | Errors

```
Microsoft (R) Aarts v1.0 Compiler v1.2a (2002/01)
Copyright (C) Microsoft Corporation. All rights reserved.
processing C:\Program Files\AIE\Aarts\include\runtime\prelude.aarts
processing C:\Program Files\AIE\Aarts\include\runtime\default.aarts
processing C:\Me\Opera\Talks\Aarts\Import\import.doc
Microsoft (R) Aarts v1.0 Word Extractor
Copyright (C) Microsoft Corporation. All rights reserved.
```

File Edit View Insert Format Tools Aami Table Window Help

Aami Word | Turn off Aami Word

```
  key as Integer
  asString() as String
    return "v" + asString(key)

We provide a particular input for the demo.

initializeDigraph()
  let N = [new Vertex(i) | i in [0..9]]
  V := asSet(N)
```

Aami Compiler

Output | Errors

```
Microsoft (R) Aami v1.0 Compiler v1.2a (2002/01)
Copyright (C) Microsoft Corporation. All rights reserved.
processing C:\Program Files\PSE\Aami\include\runtime\prelude.aami
processing C:\Program Files\PSE\Aami\include\runtime\default.aami
processing C:\Me\Opera\Talks\DAMSB\report\report.doc
Microsoft (R) Aami v1.0 Word Extractor
Copyright (C) Microsoft Corporation. All rights reserved.
connecting to Word...
extracting from report.doc .....
Warnings:
 unrepresentable formatting
```

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Key as Integer
asString() as String
return "v" + asString(key)
We provide a particular input for the demo.
initializeDigraph()
let N = [new VertexN(i) | i in [0..9]]
Asml Compiler
Output
Errors
validating parse tree
analyzing declarations
analyzing definitions
transforming
reducing
generating C++ code
generating object code
calling c++ compiler
tassrt.obj
4
1
2
6
0

```
  step until fixpoint
    let X = V difference asSet(H)
    if X <> {} then
      H := H - {any V | V in X where not exists u in X where E(u,v)}
```

In order to print vertices, we endow Vertex with an integer field and a printing method.

```
class Vertex...
  key as Integer
  asString() as String
    return "v" + asString(key)
```

We provide a particular input for the demo.

```
initializeDigraph()
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        (N(7),N(2)),(N(0),N(7))
}
```

This is the graphical form of the same.

```
C:\WINDOWS\system32\cmd.exe
Graph is cyclic.
Press any key to continue . . .
```

```
x where X(u,v))]
```

```
nteger field and a
```

```
let N = [new Vertex(i) | i in [0..9]]
V := set(N)
E := {(N(6),N(0)),(N(2),N(0)),(N(8),N(2)), (N(5),N(1)), (N(5),N(2)),
      (N(3),N(1)),(N(1),N(0)),(N(9),N(1)),(N(9),N(4)),(N(4),N(0)),
      (N(7),N(2)),(N(0),N(7))
}
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This is the graphical form of the same.

Topsort

-
- (a more OO version)

```
class Vertex
```

This is an abstract class at this point - no fields or methods. We don't know what vertices are.

```
structure Digraph
  V as Set of Vertex
  E as Set of (Vertex,Vertex)
```

```
structure Digraph...
  topsort() as Seq of Vertex
    var S as Seq of Vertex = []
    step until fixpoint
      let U = V difference asSet(S)
      if U <> {} then
        S := S + [(any v | v in U where not(exists u in U where E(u,v)))]
    step
      return S
```

In order to print vertices, we endow Vertex with an integer field and a printing method.

```
class Vertex...
  key as Integer
  asString() as String
    return "v" + asString(key)
```

We provide a particular input for the demo.

```
mkDigraph() as Digraph
    let V = [new Vertex(k) | k in [0..10]]
```

Theory and tools behind our approach

- ASMs: abstract state machines
- AsmL: ASM Language
- Additional tools for testing and runtime verification

ASMs

- Maximal expressivity of algorithms
  - including distributed algorithms -
  on their natural abstraction levels:
  For every algorithm A, there is an ASM B that is simulates A step for step.
  - Experimental confirmation
  - Seq and parallel (non-distributed) versions have been proved.

AsmL, Microsoft's ASM-Language

A powerful specification language

- Combines mathematical, object-oriented and component-oriented approaches
- Massively parallel
  - Closer to query languages rather than PLs in that respect
- Integrated with VS6 and VS .Net
  - A member of the .Net language family: interoperable with other .Net languages
- Integrated with MS Word, XML

An example spec

- Trusted Windows

Page Table Edit Control: An AsmL Model

Foundations of Software Engineering
Microsoft Research

December 6, 2001

Abstract

This paper uses AsmL (the Abstract State Machine Language) to describe the behavior of a proposed security component called the Page Table Edit Control.

TW.doc - Microsoft Word

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AsmL Word Turn off AsmL Word

Foundations of Software Engineering

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Abstract

This paper uses AsmL (the Abstract State Machine Language) to describe the behavior of a proposed security component called the Page Table Edit Control

Section Break (Odd Page)

Page 1 Sec 1 1/92 At 1" Ln 1 Col 1 English (U.S

start

Foundations of Software Engineering

Microsoft Research

December 6, 2001

Abstract

This paper uses AsmL (the Abstract State Machine Language) to describe the behavior of a proposed security component called the Page Table Edit Control.

Section Break (Odd Page)

The asynchrony of buffered writes by multiple processors may be a security hole. An attack based on the asynchronous behavior of the system memory bus would proceed as follows:

- Figure out a way to manipulate the write buffer so that the writes of a particular processor drain into system memory as slowly as possible. For example, perform a large number of writes so that the processor's buffer is full.
- Select an unused page frame of system memory and format it as a page table. Choose some location *loc* in the new page as the target of attack. Write a word of memory into *loc* formatted as a page table entry whose target is a trusted page. Make sure that the operation goes into a "slow write buffer" from step one above.
- In parallel with the operation given in the previous bullet, add the page frame number of the page table from the previous step as a page table entry of some directory found in `System.RPV`. Do this in such a way that the page table edit will be resolved before the buffered write from the previous step has had a chance to be drained into system memory. This will require that two processors be used, one with a busy write buffer and one with a relatively idle one. (The attack cannot be performed with just one

Spec

Validate

Comprehend

Play scenarios

Test

Model check

Prove properties

Enforce

Generate test suites

On-the-fly testing

Lockstep runtime verification

Testing with AsmL

- We are deeply involved with testing.
  - Our approach empowers testers, and they like that.
- The ITE/AsmL project
- There are powerful testing techniques for finite automata
- An ASM-to-FSM algorithm

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